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Principles to develop size ranges of products with ergonomic requirements, using a robust design approach

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Abstract

This paper presents an approach to developing size ranges of products that have ergonomic requirements. Ergonomic requirements are a main source of semi-similarity in size ranges. This approach is based on a process model for uncertainty analysis, the size range development methodology of Pahl and Beitz, and robust design principles.
The process model captures the interactions between user, the man-machine interface and the scaled product (the appliance). Interactions between user, man-machine interface and appliance can be classified as planned interactions or disturbances, and either influence or impact a variation. Using three robust design principles for elimination of disturbances and elimination or reduction of disturbance influence or impact, the synthesis of solutions for man-machine interface design can be supported. The robust design principles are adapted to the interactions of the user and the man-machine interface with the size range. The outcome is integration of the two disciplines, ergonomics and size range development.

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Keywords: Size range, scaling, robust design, ergonomics

1. Introduction

Size ranges are very common in products. They are found almost everywhere – machine elements like bolts, feather keys or gear wheels, consumer goods like TVs, refrigerators, gas turbines, aircrafts and machining centers.

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This means that many products that are developed into size ranges have man-machine interfaces (MMI) or are part of an MMI. In general, products can be scaled in size, power, capacity, speed, force, etc., to satisfy various specifications of customer need. A size range is, according to Pahl and Beitz, a product that fulfills the same purpose but is available in different sizes to cover a wide range of usage, has the same technical solution and is manufactured as similar as possible [1]. Since the geometric scaling of a product does not necessarily lead to satisfying solutions the designer has to modify the product, which leads to semi-similar series [2]. One of the most common reasons for semi-similarity is that the product has MMIs. This can be illustrated using different sized airplanes – though neither the seats nor the control stick is scaled with the plane, and the operating forces should not be scaled too much either.

Literature about size range development using laws of growth shows that ergonomics are “overriding standards” that lead to semi-similarity [3,4,5,6], though there is no specific guideline or approach to deal with ergonomic requirements in a structured way. It is only for spatial requirements that size range methodology gives instructions on how to deal with overriding standards. The situation is little better when using dimensional analysis as a method of scaling. Since dimensionless numbers can include biomechanical parameters [7], there is more support for the integration of ergonomic requirements into scaling. Nevertheless, dimensional analysis is not as efficient in size range development as laws of growth integrate preferred number diagrams and allow efficiently structured development of a size range [2].

The literature on research in ergonomics, human centered design and anthropometry has similar findings. Human capabilities (physical and informational) are described well [8,9,10], and guidelines are given for the design of workplaces, MMIs and tasks [11,12,13] or the analysis of work (only literature relevant to mechanical MMI is the focus of this paper; cognitive work is not considered here). Ergonomics and human centered design do not look at the way that fulfillment of requirements is ensured technically within a size range. Scalability in ergonomics is understood as fitting an interface or task to humans of different size, physical strength, etc. [14], not about scaling the product to fit non-ergonomic customer requirements. Usually, design of the interface is carried out. This design then hopefully fulfils requirements. Scalability, together with the product that is controlled through MMI, is not considered.

From these two perspectives the question arises of how the synthesis of size range products involving MMI can be more efficient. This paper presents an approach to structuring the dependencies between man-machine interfaces and scaled size range products. This is done using models and classifications from robust design, since scaling of the product can be modeled as disturbance to the input-output relation targeted by the MMI. The benefit of a new approach is that time and cost-intensive procedures required to develop MMI [15,16] can be simplified for sequential designs of a size range because an MMI for a basic design can be transferred with less uncertainty to a sequential design.

2. Models and Methods

The models and methods used in size range development of MMIs are given in this section. First, the size range development methodology of Pahl and Beitz [2] is introduced briefly. Modeling of processes and functions is then explained. Finally, the robust design principles used to create the procedural models for size range development, including MMI, are introduced.

2.1. SizeRange Methodology

The underlying size range methodology in this paper is the six step methodology of Pahl and Beitz [2]. Physical relations are determined and written in a dimensionless form using step factors that are ratios that describe the growth of a parameter, from basic design to sequential design. The dimensionless form of physical relations is called a law of growth. Laws of growth can be found for physical phenomena [2,5], costs [3,4] and environmental impacts [6]. The main steps of this methodology are shown in Fig. 1a. The emphasis on ergonomics is in steps four and five, where the aim is to support the synthesis of MMI in size range products already within the basic design phase. Also in this methodology, deviation of parameters or disturbances (i.e. uncertainty) can be integrated into laws of growth [17,18]. This is useful for additional modeling of the distribution of body measurements when integrating anthropology into laws of growth.

2.2. Process Model

Processes that have to be scaled are the main reason for developing size range products. For example, customers demand trucks with different load capacities for different transport tasks, machine tools for different sized work pieces and different powers of motors in a car to achieve different acceleration. Many of these scaled processes require interaction with a user. The user of a machine tool needs to insert raw material into the machine, change tools and program the controller or control the process. The process is realized by appliances during use [19]; the user may interact with the process as well as with the appliance. A model that captures the interaction of processes with appliances in detail is the Collaborative Research Centre SFB 805 process model. In its basic version [20], the appliance is a black box model based on the process model of Heidemann [21], which is sufficient to model the man-machine interaction to a satisfactory degree of concretization. Therefore, the modified process model of Freund [22] is used (Fig. 1b). This model refers to the appliance not as a black box but as a detailed system, modeled with blocks that form a block diagram or function structures [22].

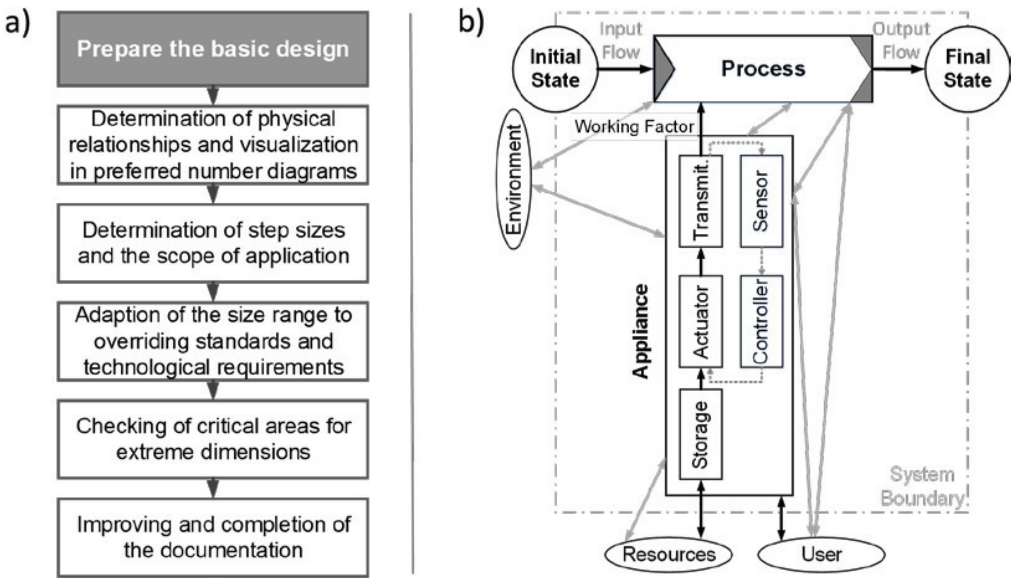

Fig. 1. (a) Procedural steps of size range development, according to Pahl and Beitz [2]; (b) Process model with detailed modeling of the appliance, according to Freund et al. [22]. Vertical and horizontal arrows represent planned interaction; sloped arrows represent disturbances.

2.3. Robust Design Principles

Robust design is part of quality engineering [23]. Variability in environmental factors (Taguchi calls it 'noise factors') can create quality problems and stop a product from working properly. Rather than trying to control noise factors, robust design aims to create products that are not sensitive to noise factors. Andersson shows that the best possibility of creating a robust product is using robust system design, not just a proper tolerance design [24]. Various strategies and principles that are meant to lead to a robust design are found in literature [24,25,26,27]. Most of them are for specific products only; for example, the principles of Mathias [27] are general principles that address functions, rather than working principles. Since MMI in size range products is not focused on working principles [24], taxonomy [26] nor electromagnetic effects [25], the approach of Mathias will be the basis for further explanations.

The basis of the RD principles of [27] is the understanding that the environment creates disturbances,which is fully compatible with modeling them in the process model (Section 2.2). These disturbances affect the product, which is called the influence of the disturbance. The influence of the disturbance has a powerful impact on the product, possibly leading to reduced product function or disturbedproduct behavior. The principles proposed in [27] are "*eliminate disturbance*", "*reduce/eliminate disturbance influence*" and "*reduce/eliminate disturbance impact*". They are ordered from avoidable to preferable, as shown in Fig. 2. The three principles cannot be separated from each other. In fact, they are based on each other. For a more detailed derivation of these principles, including examples, see [27].

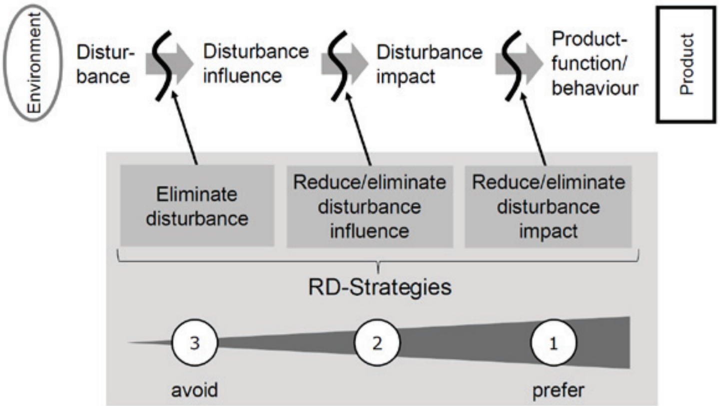

Fig. 2.Robust Design Strategies, as in Mathias et al. [27].

3. Design Approach

The following assumptions are made when developing a design approach that aims for an integrated view of ergonomics and size range development, using the principles of robust design:

- Growth of the appliance in size or power, as occurs in size ranges, affects man-machine interaction.
- Deviations in human or appliance parameters that affect the MMI are modeled as disturbances.
- To enable detailed analysis, the appliance is split into functions or a block diagram, showing modules or areas of the design.

Methods from ergonomics create an MMI that is suitable for a certain task. If the MMI is optimized for medium-sized design of the size range, maximum compatibility or a minimum of adaptive design work is ensured. Because of this, medium sizes are preferred for the basic design of a size range [2]. Since methods from ergonomics tend to neglect the technical relations that do not directly interfere with the MMI, not scaling the MMI is desirable. A reasonable exception would be if a geometrically similar product satisfies the ergonomic requirements of all sequential designs, or at least most of them, leading to minor additional design effort (adaption of particular sequential designs) and only minor additional costs through higher complexity in production. Looking at the size range development process, the clear aim is to keep the whole size range as geometrically similar as possible, reducing design effort and making maximum use of the similarity relations [2, 3, 5]. Since the MMI is directly dependent on the user and the process model is a model of technical processes, detailed design of the MMI can be excluded. Only its function structure or a block diagram is important in size range development. The scaled appliance and the scaled process can be modeled abstractly while including the MMI block. For size range development, it is still necessary to determine the physical relations and derive the laws of growth for dimensioning (which is not in this paper).

The important part of the process model is the interaction between user and appliance. Interaction between user and appliance can be divided into two categories. First, there is the planned interaction, for example, a force that the user provides to push a lever, button, etc., as well as information that has to be processed by the user. The second type of interaction can be modeled as disturbance, for example, if the user spills a glass of water on the interface. This kind of disturbance is not directly relevant to size range development (it is relevant to the basic design). Of more relevance would be another type of disturbance: variance in force that a user can apply, caused be exhaustion, changing environment or different users. This paper only deals with the planned interaction and disturbances of the second type.

Generic modeling, as in [22], follows from these assumptions (Fig. 3). The new model distinguishes between product functions that are part of the MMI and product functions that do not belong to the MMI. Planned interaction is represented by horizontal or vertical arrows, disturbances by sloped arrows. In Fig. 3 only the disturbances that affect the user are displayed, all other disturbances related to environment and resources can be included if it is beneficial.

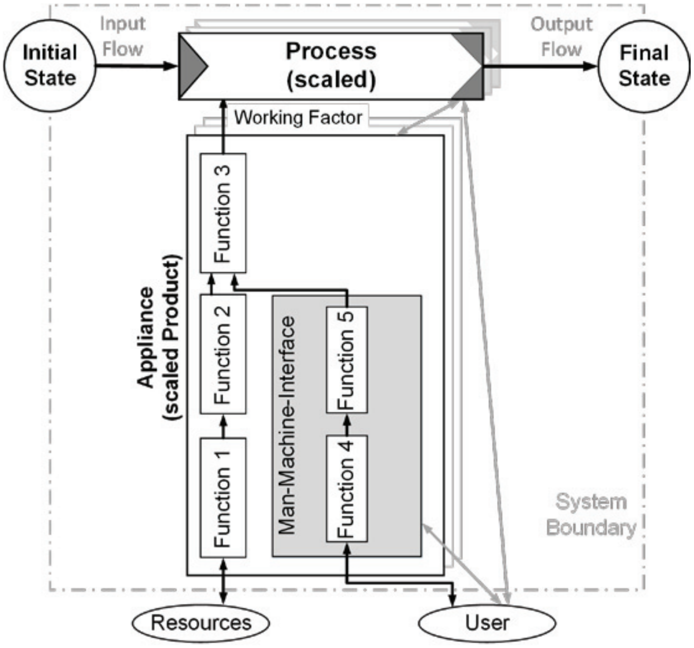

Fig. 3. Generic process model for scaled products with MMI, based on the process model of Freund et al. [22].

Bringing this model together with the robust design principles of Mathias et al. [27] (Fig. 2) means that conclusions have to be drawn from previous thoughts. The main aim is the interaction between the MMI and the rest of the appliance, which can be seen in the generic model (Fig. 3) as the arrow from “Function 5” to “Function 3”, as well as the interaction between the user and the MMI (“Function 4”). From a size range development perspective, the appliance should retain similarity. The input into the first non-MMI function (Function 3) should be as determined as possible. The level of deviation from the planned value that this input has is the impact of a disturbance by the user. From an ergonomics perspective, interaction between the product (represented by the MMI) and the user should be as determined as possible. Depending on the way this problem is approached, a varying interaction between MMI and the rest of the appliance (disturbance by the user) or between user and MMI (the scaled appliance is the disturbance for the MMI) can be seen as the impact of an occurring disturbance. The other end represents the influence of a disturbance (altering user, scaled appliance and process).

The three principles can then be applied:

- *Eliminating the disturbance* can either be by automation from the product perspective or non-scaling of the product from the user perspective (which is usually not an alternative because not scaling the product would mean that the process could not be scaled). As in Mathias, this is often the least preferable alternative since the user may still be needed for control purposes and not scaling a process will not be acceptable in most cases.

- *Reducing/eliminating the influence of the disturbance* can be achieved using different transmission ratios between MMI and the rest of the appliance. The force a user has to provide might stay constant, but the movement will be extensive. This principle is also not the most preferable since the limited capability of the power-providing user limits the power that the appliance can supply to the process. Seeing the scaled appliance as disturbance to the user, the appliance could be designed in such a way that the transmission function between process and user is as independent from the scaling factor as possible. This is often not possible, especially if the user is the main energy source for the process.
- *Reducing/eliminating the impact of the disturbance* can be achieved if the user is not a necessary energy source for the process but just provides informational interactions (generating signals by pressing buttons is considered informational here since the physical effort is not the primary source of exhaustion for the user, nevertheless, one-sided dynamic muscular work has to be considered in the basic design of a size range). In this case, the signal that is generated by the user is transformed by the MMI into a signal that the rest of the appliance can convert into the working factor, using energy from the resources. This design uncouples the user from the appliance, which is desirable in size range development since signals are constant over the size range (frequencies may change). If the product is adaptive, the user can be employed to provide work but, depending on the scale factor and the user, the appliance supports the user by adding energy over an actuator.

The example product is a manual bending machine that is used to form sheet metals. The bending force F is provided manually by the user. The thickness of the sheets that can be bent depends on the strength of the sheet material and the length of the lever, which determines the transformation ratio between user manual force and the bending force. A diagram showing the working principle is provided in Fig. 4.

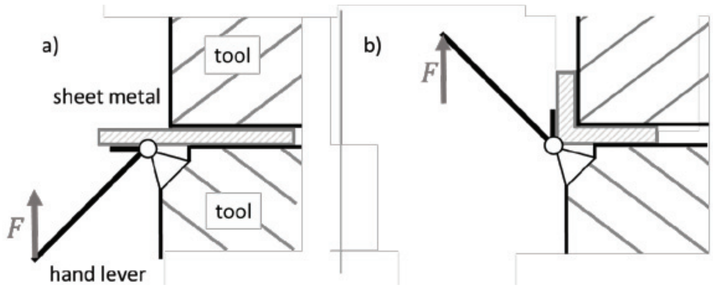

Fig. 4. (a) Initial state of the manual bending process; (b) final state of the manual bending process.

For this example product, the principles of RD can be applied to the interaction between User, MMI and the rest of the appliance. Three possible solutions for the three principles can be derived. The process models the basic design (Fig. 5a) as an automated version, first principle (Fig. 5b); a version with an adjustable transmission (additional to the existing lever), second principle (Fig. 5c); and a version that decouples the user energetically.

4. Conclusion

This paper shows that process-based modeling is a feasible way to integrate man-machine interaction and size range development. Classifying the interactions between user, MMI and the scaled appliance as planned interaction or disturbance allows solutions to be found that fulfill ergonomic requirements by keeping the interface and design as constant as possible during scaling. Depending on the requirements that have to be fulfilled, one of three principles can be chosen. The principles cannot be prioritized as strictly as in [22] in size range development, but a guideline can be given: the more an MMI decouples the user from the product, the easier it is to retain similarity in the appliance while providing an MMI that is constant throughout the appliance size change. Technical solutions can be synthesized by varying the function structures and block diagrams in the detailed process model.

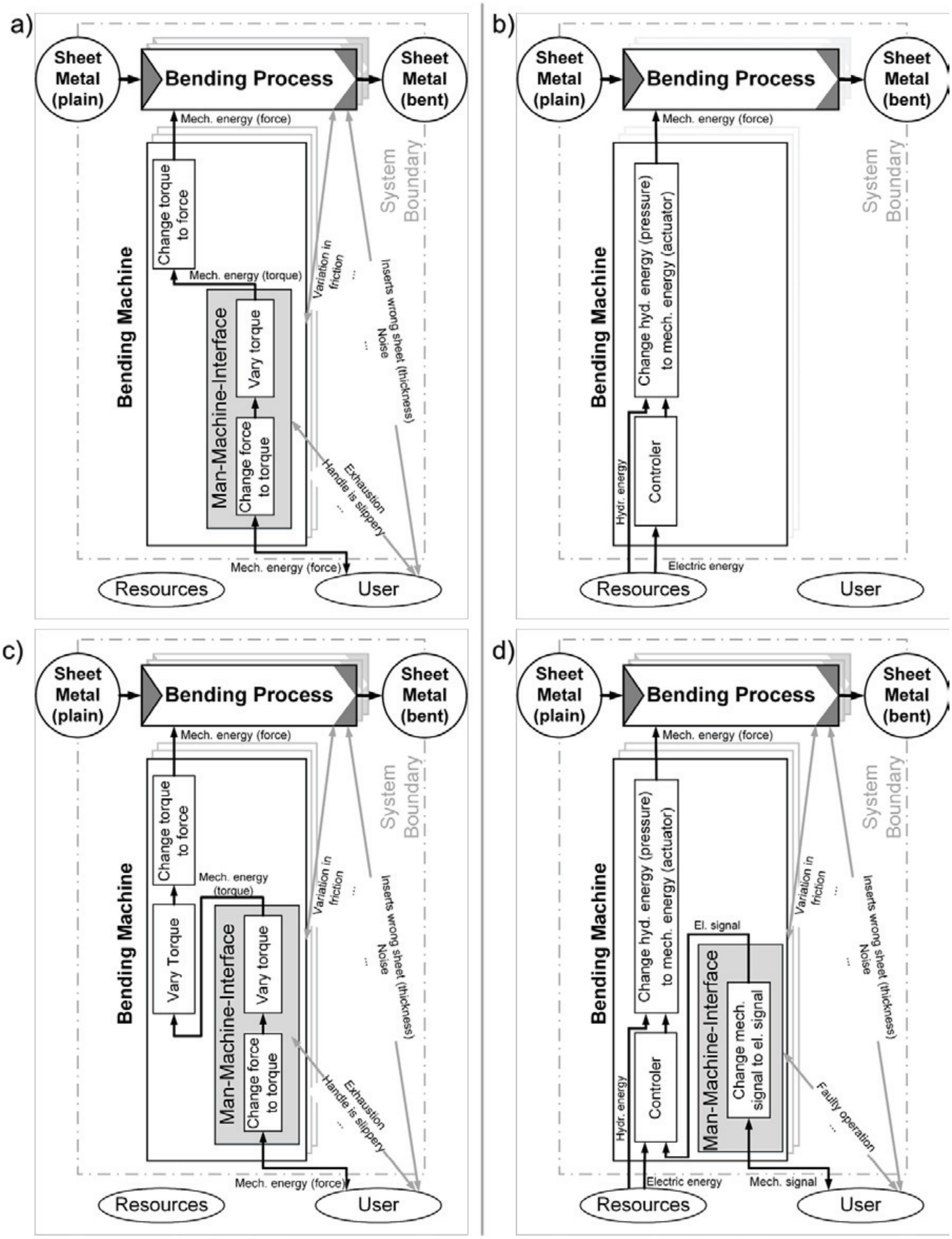

Fig. 5. (a) basic design; (b) size range, automated version/no scaling for appliance and process (light grey boxes), (c) size range with additional transmission, (d) size range with energetically decoupled user.

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